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(54) **NORMALIZATION OF INTELLIGENT TRANSPORT SYSTEM HANDLING CHARACTERISTICS**

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G05D 1/02 (2020.01)
G05D 1/00 (2006.01)

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CPC ***G05D 1/0276*** (2013.01); ***G05D 1/0088*** (2013.01); ***G05D 1/0287*** (2013.01); *G05D 2201/0213* (2013.01)

(58) **Field of Classification Search**
CPC .. G05D 1/0276; G05D 1/0088; G05D 1/0287; G05D 2201/0213
See application file for complete search history.

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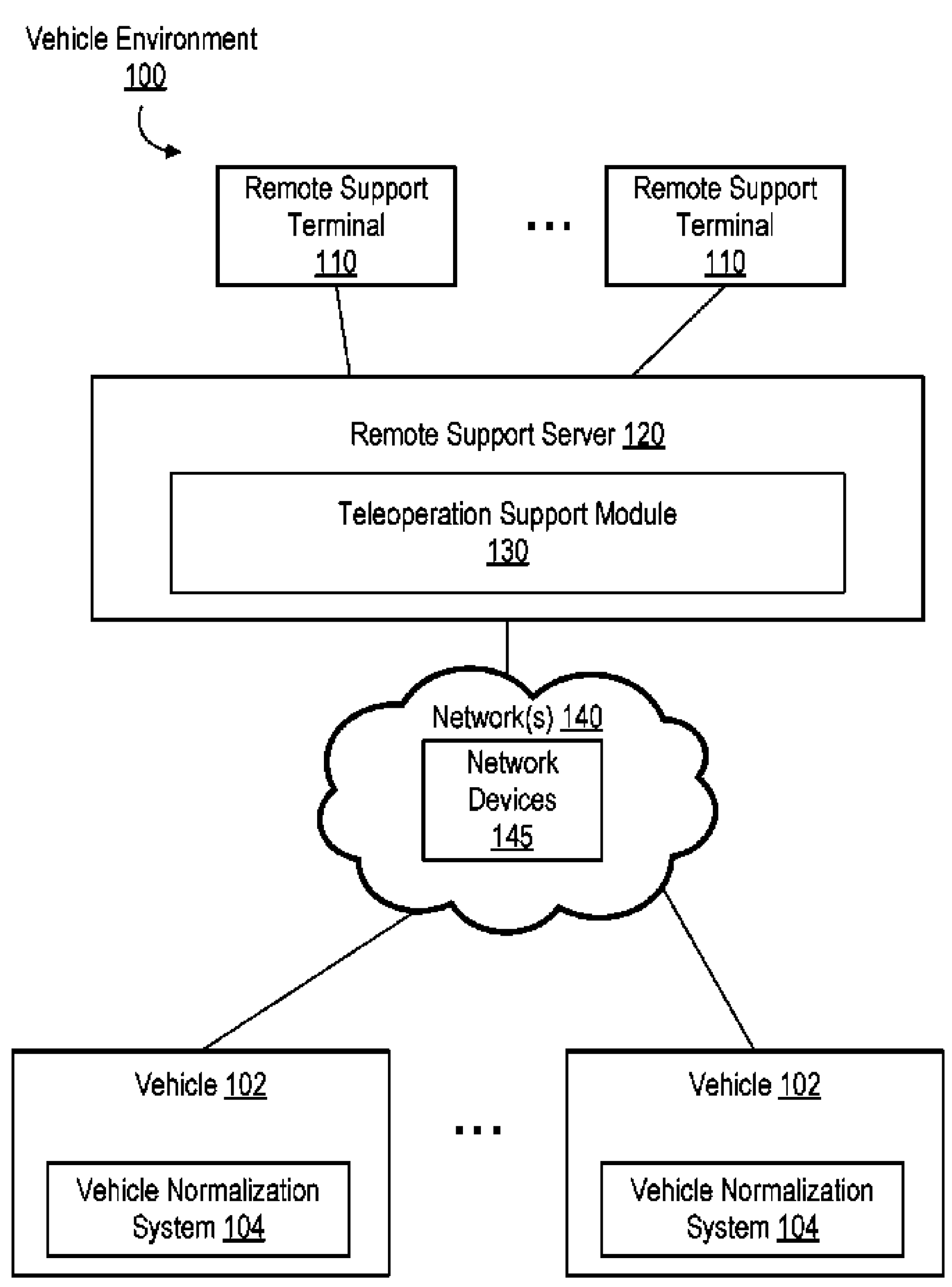
(57) **ABSTRACT**

In a vehicle system that can receive remote support from a remote support server (e.g., interfacing with a human or computer teleoperator), a local normalization engine locally normalizes operation of the vehicle based on locally available sensor data that may not be accessible to the remote support server. The local normalization engine applies transformations to control commands received from the remote support server to transform the command to compensate for conditions that are locally sensed and may be unknown to the remote support server. Alternatively, or in addition, the local normalization engine controls auxiliary functions of the vehicle (e.g., by activating one or more auxiliary actuators) that may not be under direct control of the remote support server.

20 Claims, 4 Drawing Sheets



Related U.S. Application Data

(60) Provisional application No. 62/698,765, filed on Jul. 16, 2018.

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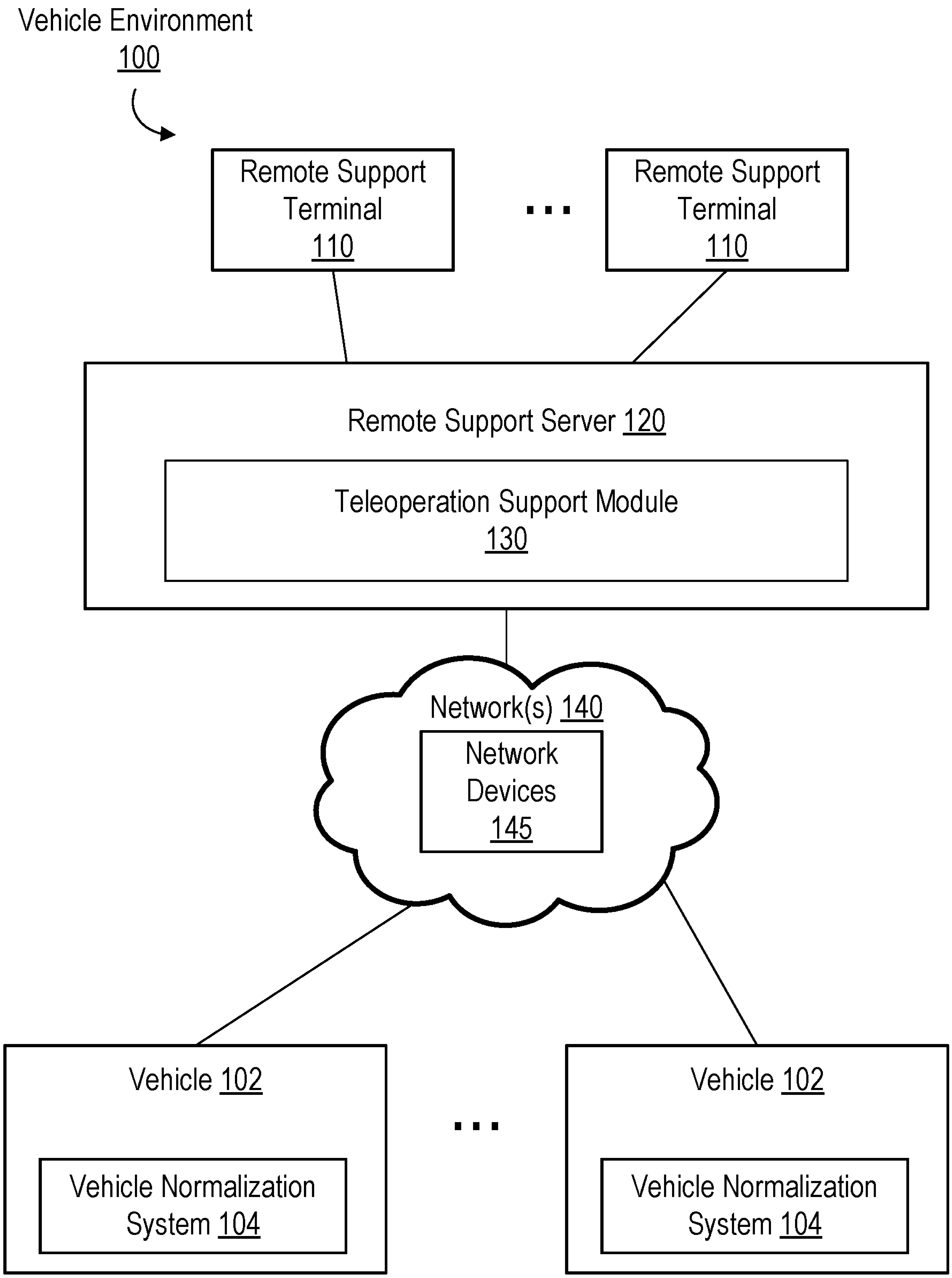
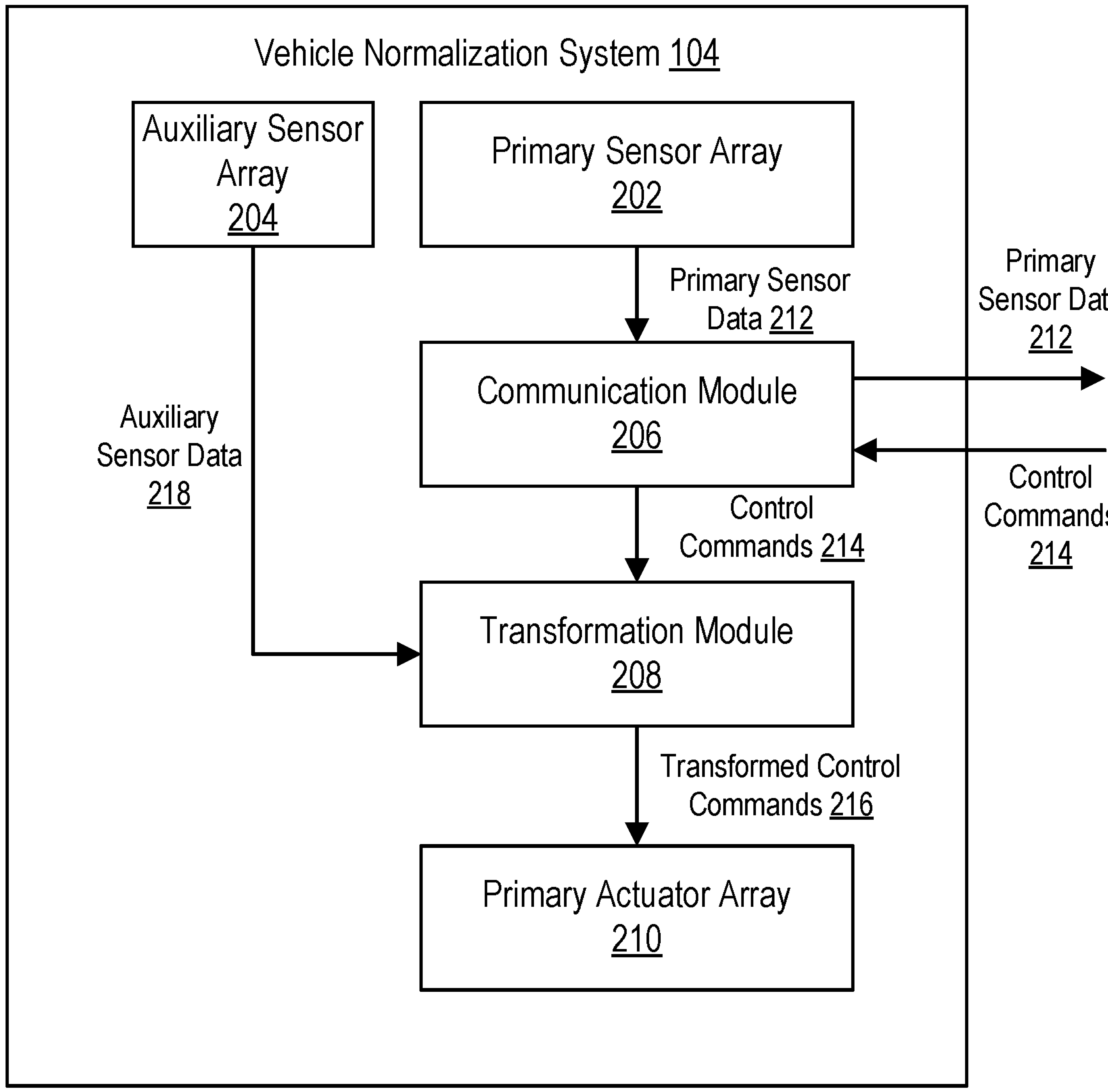

Vehicle Environment
100
Remote Support Terminal 110
...
Remote Support Terminal 110
Remote Support Server 120
Teleoperation Support Module 130
Network(s) 140
Network Devices 145
Vehicle 102
Vehicle Normalization System 104
...
Vehicle 102
Vehicle Normalization System 104

FIG. 1



Vehicle Normalization System 104
Auxiliary Sensor Array 204
Primary Sensor Array 202
Primary Sensor Data 212
Primary Sensor Data 212
Communication Module 206
Auxiliary Sensor Data 218
Control Commands 214
Control Commands 214
Transformation Module 208
Transformed Control Commands 216
Primary Actuator Array 210

FIG. 2

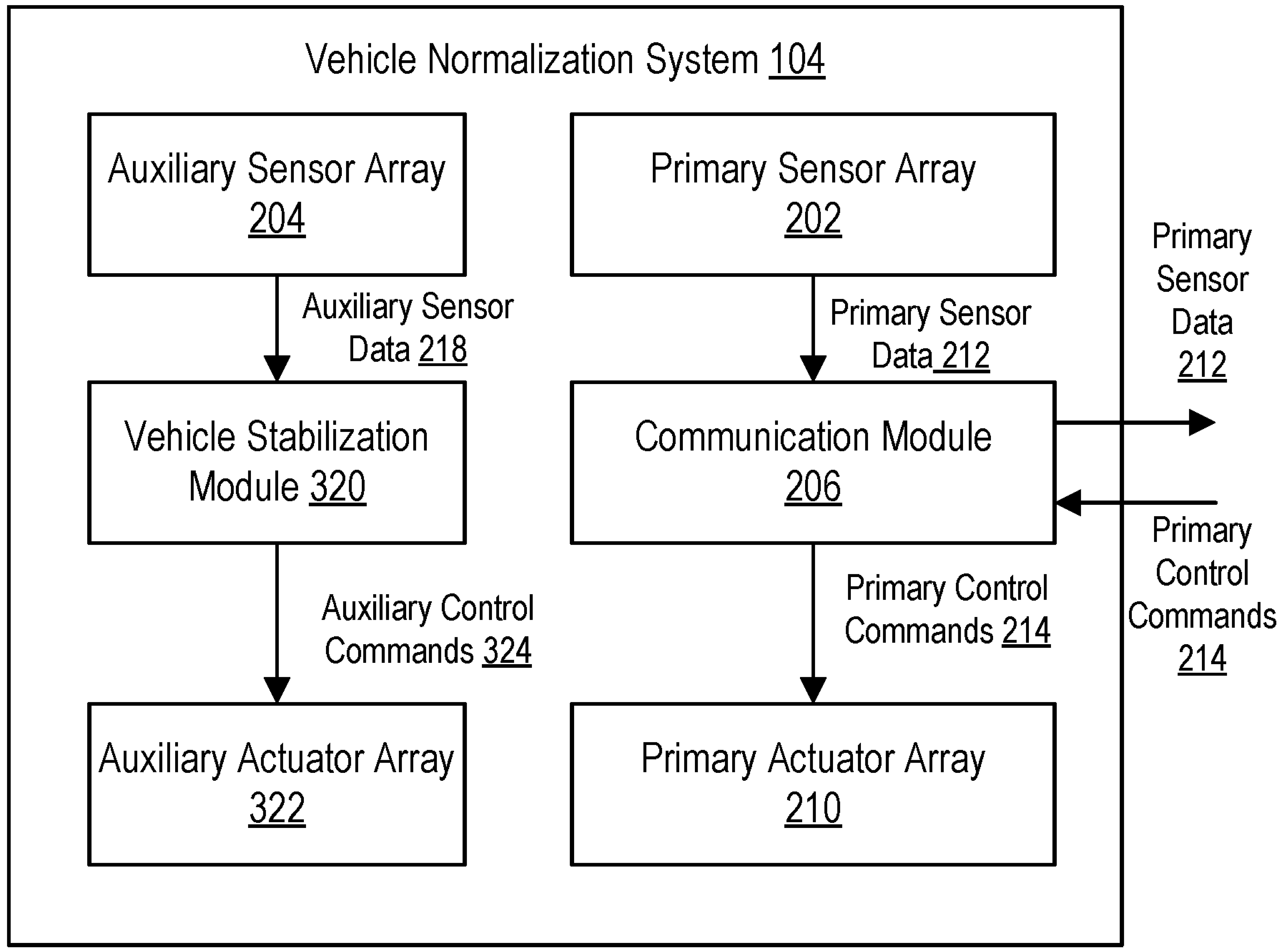

Vehicle Normalization System 104
Auxiliary Sensor Array 204
Primary Sensor Array 202
Auxiliary Sensor Data 218
Primary Sensor Data 212
Primary Sensor Data 212
Vehicle Stabilization Module 320
Communication Module 206
Auxiliary Control Commands 324
Primary Control Commands 214
Primary Control Commands 214
Auxiliary Actuator Array 322
Primary Actuator Array 210

FIG. 3

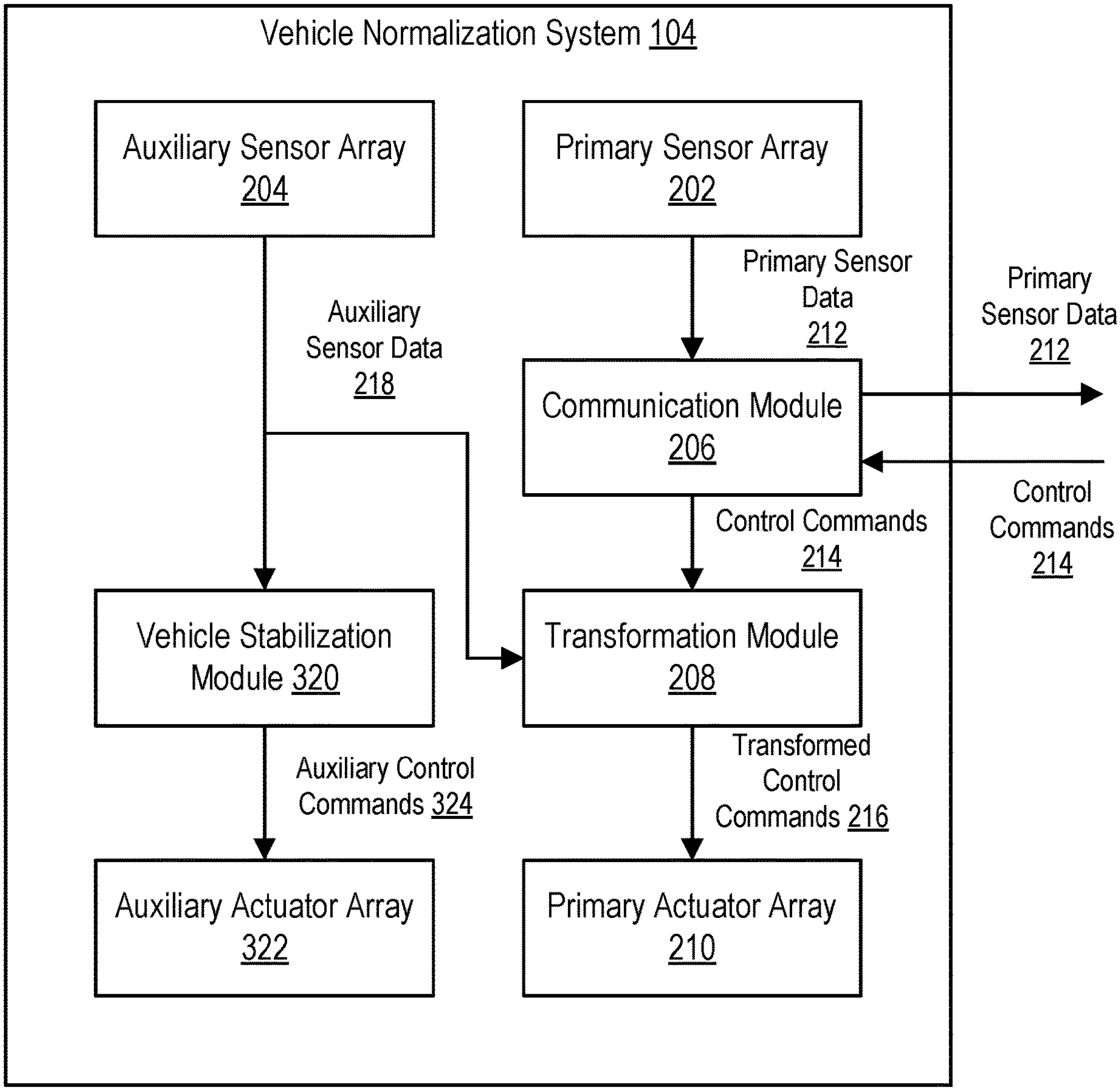

Vehicle Normalization System 104
Auxiliary Sensor Array 204
Primary Sensor Array 202
Primary Sensor Data 212
Auxiliary Sensor Data 218
Primary Sensor Data 212
Communication Module 206
Control Commands 214
Control Commands 214
Vehicle Stabilization Module 320
Transformation Module 208
Auxiliary Control Commands 324
Transformed Control Commands 216
Auxiliary Actuator Array 322
Primary Actuator Array 210

FIG. 4

NORMALIZATION OF INTELLIGENT TRANSPORT SYSTEM HANDLING CHARACTERISTICS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 16/509,464 filed on Jul. 11, 2019, now U.S. Pat. No. 11,216,007 issued on Jan. 4, 2022, which claims the benefit of U.S. Provisional Patent Application No. 62/698,765 filed on Jul. 16, 2018, both of which are incorporated by reference herein.

BACKGROUND

1. Technical Field

The disclosed embodiments relate generally to remotely controlled vehicles, and more specifically, to a system for normalizing operation of a vehicle receiving control signals from a remote support system.

2. Description of the Related Art

Recent advances in autonomous vehicle technologies promise to revolutionize all kinds of ground transportation, including private motor cars, cargo truck fleets, and the taxi industry. Achieving a safety level of such intelligent transport systems (ITS) at least equal to that of experienced human drivers and eventually surpassing it is the foremost concern of ITS developers.

One of the latest trends in ITS technology is development of always-online vehicles that keep a running connection to a remote server in order to transmit telemetry and video feeds. Such feeds can then be used either in offline mode for tasks such as incident analysis or for real-time processing by a human operator, machine intelligence agent, or a combination thereof to remotely operate the vehicle. In remote teleoperation scenarios, it is important for safety considerations to enable the remote server to receive the video and/or telemetry in real-time and for the vehicle to similarly receive driving commands in real-time from the server. However, a challenge exists in maintaining sufficiently low latency given the bandwidth constraints of wireless networks and the significant amount of data that may be associated with vehicle operation. Furthermore, a challenge exists in managing inconsistencies between handling characteristics of different vehicles or environmental conditions associated with a given teleoperation scenario.

SUMMARY

A vehicle system obtains primary sensor data from a primary sensor array of a vehicle and communicates the primary sensor data to a remote support server. In response to the primary sensor data, the vehicle system receives control commands from the remote support server for controlling a drive system of the vehicle. The vehicle system also obtains auxiliary sensor data from an auxiliary sensor array of the vehicle. The vehicle system transforms the control commands based on sensed conditions derived from the auxiliary sensor data to generate transformed control data. The vehicle system controls a primary actuator array based on the transformed control commands to control driving of the vehicle.

In an embodiment, the vehicle system furthermore determines, based on the auxiliary sensor data, that a parameter defining the state of the vehicle or a plurality thereof is outside a predefined range and generates vehicle stabilization commands that operate to restore the out of bounds parameters to within the respective predefined ranges. The vehicle system may control an auxiliary actuator array to execute the vehicle stabilization commands.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram illustrating an example embodiment of a vehicle environment.

FIG. **2** is a block diagram illustrating a first embodiment of a vehicle normalization system.

FIG. **3** is a block diagram illustrating a second embodiment of a vehicle normalization system.

FIG. **4** is a block diagram illustrating a third embodiment of a vehicle normalization system.

DETAILED DESCRIPTION

In a vehicle system that can receive remote support from a remote support server (e.g., interfacing with a human or computer teleoperator), a local normalization engine locally normalizes operation of the vehicle based on locally available sensor data that may not be accessible to the remote support server. In a first embodiment, the local normalization engine applies transformations to control commands received from the remote support server to transform the commands to compensate for conditions that are locally sensed and may be unknown to the remote support server. In a second embodiment, the local normalization engine controls auxiliary functions of the vehicle (e.g., by activating one or more auxiliary actuators) that may not be under the direct control of the remote support server. The functions may serve to stabilize a sensed condition of the vehicle that may be unknown to the remote support server or that cannot be controlled by the remote server. In a third embodiment, a combination of command transformations and auxiliary operations may be employed. The described vehicle system may enhance safety by enabling a remote operator to issue commands based on a consistent, quasi-stationary model of a vehicle while compensating for deviations locally. This architecture may beneficially limit data transmitted from the vehicle to the remote support system to core sensor data (e.g., real-time video) and limit data transmitted from the remote support system to the vehicle to core driving commands such as steering, acceleration, and braking commands. By limiting the data transmitted between the vehicle and the remote support server to those utilized for core functions, problems associated with bandwidth limitations and latency constraints can be reduced or eliminated while enabling safe vehicle operation.

FIG. **1** is a block diagram of a vehicle environment **100** including a plurality of vehicles **102**, a remote support server **120** optionally coupled to one or more remote support terminals **110**, and one or more networks **140** comprising network devices **145**. In alternative embodiments, the vehicle environment **100** may include different or additional components.

The vehicle **102** comprises a land vehicle (e.g. a car or truck), a seaborne vehicle, a subterranean vehicle, an airborne vehicle, or other vehicle. The vehicle **102** may comprise an intelligent transport system (ITS) that connects to one or more networks **140** and communicates with one or more entities via the one or more networks **140** (e.g., the remote support server **120** and/or other vehicles **102**) to enable the vehicle **102** to obtain information useful to safe navigation of an environment. In an embodiment, the vehicle **102** may comprise an autonomous or semi-autonomous vehicle that includes an autonomous driving system that automatically controls navigation based on sensed environment conditions. Alternatively, the vehicle **102** may include a non-autonomous vehicle that relies on control inputs from a driver in the vehicle **102** or from the remote support server **120**. In the case of teleoperation, the vehicle **102** wirelessly receives control inputs via the one or more networks **140** that control various components of the drive system such as the steering system, acceleration, braking, etc. The vehicle **102** may also comprise various sensors that capture image data and other environmental data that may be streamed over one or more networks **140** to a remote support server **120** or to other vehicles **102**.

The remote support server **120** includes a teleoperation support module **130** that communicates with a vehicle **102** to provide remote teleoperation or other support services. The teleoperation support module **130** may be implemented as one or more non-transitory computer-readable storage mediums that stores instructions executed by one or more processors to perform the functions attributed herein.

In an embodiment, the teleoperation support module **130** may provide teleoperation support in instances when extra assistance is desired. For example, the vehicle **102** may request teleoperation assistance from the teleoperation support module **130** when one or more vehicle sensors fail, when an unknown problem occurs with the vehicle's autonomous driving software, when the vehicle **102** encounters a barrier or other hazardous road conditions, or when a passenger manually requests remote assistance. Furthermore, the teleoperation support module **130** may provide teleoperation support when the vehicle **102** enters a geographic region where it is not legally permitted to operate in a completely autonomous way.

In an embodiment, upon requesting remote support, a video stream capturing the vehicle environment may be provided by the vehicle **102** to the teleoperation support module **130** and presented at a remote support terminal **110**. A human teleoperator at the remote support terminal **110** may view the video stream on a display to assess the situation and take appropriate action via a control input device at the remote support terminal **110**. In this embodiment, the teleoperation support module **130** may present real-time video streamed from the vehicle **102** to a display of the remote support terminal **110** and may provide real-time control data to the vehicle **102** received via the remote support terminal **110** to enable the teleoperator remotely drive the vehicle **102**.

In another embodiment, the teleoperation support module **130** may comprise an artificial intelligence agent that does not necessarily require a remote support terminal **110** with a display or physical controls for providing human input. Here, the teleoperation support module **130** may provide control instructions to the vehicle **102** directly based on the processing of a real-time video feed and other sensor data streamed to the teleoperation support module **130** from the vehicle **102** without necessarily utilizing any human input. In alternative embodiments, the teleoperation support module **130** may comprise a semi-robotic agent that interacts with a remote support terminal **110** in a similar manner as a human teleoperator.

In other embodiments, the remote support server **120** may provide different support to the vehicle **102** that does not necessarily involve teleoperation. For example, the remote support server **120** may provide voice support to a driver or passenger of the vehicle **102** in response to video or other sensor data received from the vehicle **102**. In other cases, the remote support server **120** may provide navigation services to re-route a vehicle **102** or otherwise assist a vehicle **102** in navigating to a destination. In other examples, the remote support server **120** may provide software or firmware updates to a vehicle **102**.

The remote support terminals **110**, if present, may be coupled to the remote support server **120** via a local area network connection, a direct wired connection, or via a remote connection through the network **140**. A remote support terminal **110** may include a display to enable a human teleoperator to view real-time video of the vehicle environment and controls for enabling a human teleoperator to control the vehicle. In an embodiment, the video may include at least a front view that mimics or approximates the view seen by a driver within the vehicle **102**. Optionally, the video may include additional views, such as a rear view video, side view videos, or other views that may mimic the views seen by a driver in mirrors of a traditional vehicle or may include other views not necessarily available to a driver of a traditional vehicle. The controls may include controls that mimic those available within a traditional vehicle such as a steering wheel, acceleration pedal, and brake pedal. Alternatively, different forms of controls may be available at the remote terminal **110** such as a joystick, mouse, touch screen, voice control system, gesture control system, or other input mechanism to control one or more aspects of the vehicle **102**.

In other embodiments, where the teleoperation support module **130** operates entirely as an artificial intelligence agent without human intervention, the remote support terminals **110** may be omitted.

The plurality of networks **140** represents the communication pathways between the vehicles **102**, the remote support terminals **110**, and the remote support server **120**. In one embodiment, the networks **140** use standard communications technologies and/or protocols and can include the Internet. In another embodiment, the entities on the networks **140** can use custom and/or dedicated data communications technologies. The plurality of networks **140** may comprise networks of different types such as, for example, a public cellular connection, a dedicated or private wireless network, a low-latency satellite uplink, VANET wireless channels (including vehicle-to-vehicle or vehicle-to-infrastructure links), or any combination thereof. Furthermore, the plurality of networks **140** may include multiple networks of the same type operated by different service providers. The network devices **145** may include cell towers, routers, switches, LEO satellite uplink devices, WiFi hotspot devices, VANET devices, or other components that provide network services to the entities connected to the plurality of networks **140**. The network devices **145** may be integrated into roadside infrastructure units that are integrated with traffic devices or other roadside systems. The network devices **145** may have varying capabilities and may be spread over a wide geographic area. Thus, different allocations of network resources may be available to vehicles **102** in different locations at different times depending on environmental factors, the capabilities of different network devices **145**, and network congestion in the area where each vehicle **102** is located.

In an embodiment, the vehicle **102** includes a vehicle normalization system **104** that locally normalizes operations of the vehicle **102** to enhance safety and improve overall operation of the vehicle **102**. The vehicle normalization system **104** may locally compensate for characteristics of the vehicle, local environment conditions, or other factors, at least some of which may not be available to the remote support server **120**. By normalizing for such conditions locally, the remote support server **120** can operate based on a standardized default kinematic model corresponding to the general class of the vehicle **102** so that the human or computer teleoperator is relieved of the task of compensating for changes in the environment and vehicle state in the decision-making process. Alternatively, the remote support server **120** or an external normalization computer (not shown) may obtain some or all of the information relating to the characteristics of the vehicle, the local environment conditions, or other factors obtained by the vehicle and the vehicle normalization system **104** may operate remotely to compensate for changes in the environment and vehicle state. Example embodiments of the vehicle normalization system **104** are described in further detail below with respect to FIGS. **2-4**.

FIG. **2** is a first embodiment of a vehicle normalization system **104** that may be embodied within the vehicle **102**. The vehicle normalization system **104** comprises a primary sensor array **202**, an auxiliary sensor array **204**, a communication module **206**, a transformation module **208**, and a primary actuator array **210**. In alternative embodiments, the vehicle normalization system **104** may include different or additional components.

The primary sensor array **202** and the auxiliary sensor array **204** may each include one or more sensors for sensing conditions relevant to vehicle operation. The primary sensor array **202** may include sensors that produce sensor data utilized by a remote support server **120** to enable remote teleoperation of the vehicle **102**. Generally, to enable teleoperation within limited bandwidth constraints, the primary sensor array **202** may include only a limited number of sensors sufficient to enable the remote support server **120** to make timely and accurate decisions for teleoperating the vehicle **102**. For example, the primary sensor array **202** may be limited to one or more cameras without including other types of sensors. Alternatively, the primary sensor array **202** may include one or more cameras and a limited number of other basic sensors.

The auxiliary sensor array **204** includes a group of sensors that generate auxiliary sensor data **218** available locally at the vehicle **102**. The auxiliary sensor array **204** may include some sensors that overlap with the primary sensor array **202** but may also include other sensors that produce auxiliary sensor data **218** that is not necessarily provided to the remote support server **120**. For example, the auxiliary sensor array **204** may include one or more cameras, LIDAR or RADAR sensors, an accelerometer, an orientation sensor, a velocity sensor, one or more temperature sensors, tire pressure sensors, engine oil sensors, wind sensors, traction control sensors, light sensors, road tilt sensors, road surface sensors, hydroplaning detection sensors, visibility sensors, weather sensors, or other sensors for detecting vehicle conditions, environmental conditions, or conditions affecting one or more occupants of the vehicle **102**. In an embodiment, some sensors (e.g., cameras) may be included in both the primary sensor array **202** and the auxiliary sensor array **204**.

In an embodiment, the sensor arrays **202**, **204** may include one or more processing devices to process raw sensor data to convert the raw sensor data to other forms of data. For example, traction control data may be derived from other sensed data such as acceleration and orientation data. In another example, road conditions may be derived from image analysis performed on image data captured by one or more cameras. Data conversion may be performed using an analytic software engine based on known physical principles, an appropriately trained artificial neural network, or using any other suitable method.

The primary sensor array **202** generates primary sensor data **212** that is provided to a communication module **206**. The communication module **206** comprises a network interface for communicating the primary sensor data **212** to the remote support server **120** via the network **140** and for receiving control commands **214** from the remote support server **120** via the network **140**. Here, the control commands **214** may include steering commands, acceleration commands, braking commands, or other control data provided by the remote support server **120** to control aspects of the vehicle operation.

The transformation module **208** obtains the control commands **214** received by the communication module **206** and the auxiliary sensor data **218** generated by the auxiliary sensor array **204**. The transformation module **208** analyzes the effect of the control commands **214** received from the remote support server **120** and applies a transformation to the control commands **214** based on the auxiliary sensor data **218** that may not necessarily be available to the remote support server **120**. The transformation module **208** may therefore compensate for differences in the expected conditions on which the control commands **214** are based and actual conditions derived from the auxiliary sensor data **218** such that the intended effect of the control commands **214** can be achieved. Thus, the transformation module **208** may predict an intended effect of a received control command **214**, and modify the control command **214** to generate transformed control commands **216** predicted to achieve the intended effect given the actual sensed conditions. Additionally, the transformation module **208** may operate to maintain certain operational parameters within a predefined range to ensure safety. For example, the transformation module **208** may generate the transformed control commands **216** to ensure that change in steering angle or acceleration do not exceed predefined limits.

In an embodiment, the transformation module **208** applies a machine-learned model to transform the control commands **214** to the transformed control commands **216**. Here, a training process may learn the model by learning correlations between features of a vehicle state (e.g., parameters of the vehicle and environmental conditions) and handling characteristics in response to different control commands **214**. The machine-learned model, when applied, may then compensate the control commands **214** based on differences between the actual vehicle state and a default vehicle state applied by the remote support server **120** when generating the control commands **214** for teleoperation.

In an embodiment, the transformation module **208** may generate a sequence of transformed control commands **216** that may include fewer or additional commands relative to the received control commands **214**. For example, in response to a steering command to execute a turn when the vehicle is accelerating down a hill, the transformation module **208** may generate both braking and steering commands to compensate for the downhill trajectory and maintain safety parameters.

The transformed control commands **216** are provided to a primary actuator array **210** to control operation of the vehicle **102**. For example, the primary actuator array **210** may comprise a steering actuator to control a steering angle, an acceleration actuator to control acceleration of the vehicle **102**, and a braking actuator to control braking of the vehicle **102**. The primary actuator array **210** thus carries out the transformed commands to achieve the intended effect of the control commands **214** issued by the remote support server **120**. In an embodiment, the primary actuator array **210** may include both physical actuators and software-based actuators that may achieve some control objective (e.g., modifying a camera setting) without necessarily controlling a mechanical element.

In other embodiments, the transformation module **208** may operate to issue commands to the primary actuator array **210** in the absence of control commands **214** from the remote support server **120**. For example, in some scenarios, the control commands **214** may become unavailable due to issues such as disrupted network connectivity, the remote support server **120** or vehicle **102** estimating a latency that is too high to allow safe teleoperation, the current telemetry feed lacking sensor data to enable safe teleoperation, or the remote support server **120** lacking access to commands necessary to safely teleoperate the vehicle **102**. To facilitate better vehicle safety in such scenarios, it is desirable for the vehicle **102** to be able to override commands issued by the remote support server **120**, if any, and to execute actions to avoid or mitigate the potential emergency.

FIG. **3** illustrates an alternative embodiment of a vehicle normalization system **104**. In this embodiment, instead of transforming the commands received from the remote support server **120**, a separate stabilization process is performed to independently control an auxiliary actuator array **322** in a manner that maintains certain sensed conditions within constrained ranges. The embodiment of FIG. **3** includes a primary sensor array **202**, an auxiliary sensor array **204**, a communication module **206**, a vehicle stabilization module **320**, a primary actuator array **210**, and the auxiliary actuator array **322**. Alternative embodiments may include different or additional modules.

The primary sensor array **302** generates primary sensor data **212** that is communicated to the remote support server **120** by the communication module **206** as described above. The communication module **206** furthermore receives primary control commands **214** from the remote support server **120** and controls a primary actuator array **210** (e.g., steering, braking, and acceleration) based on the primary control commands **214**.

The vehicle stabilization module **320** receives the auxiliary sensor data and applies a vehicle stabilization process to stabilize one or more controls aspects of the vehicle **102**. For example, the vehicle stabilization module **308** may obtain state parameters of the vehicle based on the auxiliary sensor data **218** (and/or the primary sensor data **212**), detect when a state parameter deviates from a predefined range, and generate auxiliary control commands **324** to control an auxiliary actuator array **322** to maintain the state parameters of the vehicle **102** within an expected range. The auxiliary actuator array **322** may include actuators that control aspects of the vehicle **102** different than those controlled by the primary actuator array **210**. For example, while the primary actuator array **210** may be limited to fundamental driving controls such as braking, steering, and acceleration, the auxiliary actuator array **322** may include actuators for systems such as windshield wipers, traction control systems, camera systems, or other vehicle systems that may not be directly under the control of a remote support server **120** during teleoperation of the vehicle **102**.

In further embodiments, a combination of the normalization techniques described above may be applied. For example, as illustrated in FIG. **4**, a vehicle normalization system **104** includes both a vehicle stabilization module **320** and a transformation module **208** as described above. Thus, in this embodiment, the auxiliary sensor data **218** may be processed by a vehicle stabilization module **320** to generate auxiliary control commands **324** to control an auxiliary actuator array **322** and may also be processed by a transformation module **208** to generate transformed control commands **216** based on the received control commands **214** to control the primary actuator array **210**. Here, either the vehicle stabilization module **320**, the transformation module **208**, both, or neither may be activated under different detected conditions. Thus, for example, under a first set of conditions, the vehicle stabilization module **320** may be active and the transformation module **208** is bypassed (e.g., the control commands **214** are applied directly to the primary actuator array **210** as in FIG. **3**); under a second set of conditions, the transformation module **208** is active and the vehicle stabilization module **320** and the auxiliary actuator array **322** are inactive; under a third set of conditions, both the vehicle stabilization module **320** and the transformation module **208** are active; and under a fourth set of conditions the vehicle stabilization module **320** and the transformation module **208** are both inactive.

In a further embodiment, the normalization techniques described above may be applied iteratively to achieve greater precision. For example, under a first set of conditions, the transformation module **208** may be activated and process a control command **214** or a plurality thereof issued by the remote support server **120** into a first set of transformed control commands **216** that are subsequently applied to the primary actuator array **210**. The system **104** may then acquire auxiliary sensor data **218** from the auxiliary sensor array **204** in order to measure the error between the planned motion of the vehicle **102** and the actual motion. In case the error exceeds a predefined or a computed threshold, the system **104** may then supply the transformation module **208** with the updated sensed information and re-run the transformation procedure to adjust the commands applied to the primary actuator array **210**. This cycle may be repeated multiple times until the error between the planned and sensed motion of the vehicle **102** is determined to fall below a desired threshold.

In an example use case that may employ one or more of the embodiments of FIGS. **2-4**, a vehicle **102** may be loaded with an atypical amount of cargo and this information may not be available at the remote support server **120**, which may instead be configured to issue control commands **214** consistent with a typical amount of cargo. The atypical amount of cargo may change the effect of acceleration and braking commands on the vehicle **102**. Thus, the transformation module **208** may predict the intended effect of the received acceleration and braking commands (e.g., by determining the effect of the commands on a vehicle with typical cargo) and transform the acceleration and braking commands to achieve the intended effect. For example, the acceleration and braking commands may be transformed to apply the same force to the vehicle **102** that the commands would apply to the same vehicle **102** under a typical load.

In another example use case, a vehicle **102** may be transporting a partially filled liquid tank with a substantial ullage. In this case, execution of control commands **214** may lead to significant changes of the position of the center of mass of the vehicle **102**, that may be compensated by transformation of control commands **214**. The spatial configuration of the volume of the liquid being transported may be sensed by the auxiliary sensor array **204** (for example, by sounding the liquid tank with an array of sonars), or be computed numerically or analytically using a physics modeling engine.

In another example use case, a vehicle **102** may be operating with low tire pressure. The low tire pressure may be sensed by the auxiliary sensor array **204** but may be unknown to the remote support server **120** that does not receive this information. The low tire pressure may affect how the vehicle **102** responds to steering, acceleration, or braking commands provided by a remote support server **120** on the basis of normal tire pressure, and may therefore cause the vehicle **102** to behave unexpectedly. The vehicle stabilization module **320** may activate an auxiliary actuator that causes the tire pressure to be restored to normal levels (e.g., by accessing an auxiliary compressed air tank). Alternatively, or in addition, the transformation module **208** may transform received steering, acceleration and/or braking commands that compensate for the effect on these parameters of the tire pressure being low relative to a typical expected tire pressure for the vehicle.

In another example, the auxiliary sensor data provides vehicle traction data to detect slippery surfaces such as black ice. If such a road condition is detected, the system the vehicle stabilization module **320** may activate the auxiliary actuator array **322** to extrude tire spikes, if appropriately equipped or engage a traction control system. Furthermore, the vehicle stabilization module **320** may cause the tire spikes to be retracted or disengage the traction control system when the auxiliary sensor data **218** indicates that the slippery surface is no longer present. Alternatively, or in addition, the transformation module **208** may transform the received control commands **214** to account for reduced road friction and slippage.

In another example use case, the vehicle stabilization module **320** processes the auxiliary sensor data **218** to determine approaches to tunnel entrances from either side. Usually daytime lighting conditions outdoors are markedly different from those inside a tunnel, and the onboard cameras require some time to accommodate for the change. The vehicle stabilization module **320** may precompute these predicted changes and generate commands to the auxiliary actuator array that control the camera ISO or other exposure parameters to gradually increase them as the vehicle **102** is about to enter the tunnel, and to gradually decreasing them as the vehicle is about to leave the tunnel.

In another example use case, the auxiliary sensor array **204** may include a wind sensor that detects a force or speed of gusts of lateral wind that may adversely affect the vehicle trajectory or stability. If a gust is detected that meets predefined criteria associated with a magnitude and direction of the gust, the transformation module **208** may transform received steering angle to compensate for wind effects. For example, the transformation module **208** may determine the intended effect of the received control commands **214** under typical low wind conditions, predict the actual effect of the commands under the high wind conditions, and adjust the control command **214** to generate the transformed control commands **216** to achieve the intended effect.

In another example use case, the auxiliary sensor array **204** includes sensors that determine road tilt degree and direction. Detection of an axial tilt, i.e., ascending and descending road segments, may be used by the transformation module **208** to transform acceleration and deceleration commands in the received control commands **214**. For example, when an ascending road segment is detected, an acceleration level may be increased relative to the received command and a braking force may be decreased. When a descending road segment is detected, an acceleration level may be decreased relative to the received command a braking force may be increased. Furthermore, when a lateral tilt is detected, e.g., at road curvatures, the transformation module **208** may perform velocity rebalancing and normalization of steering commands to compensate for the road tilt that may not be perceived by the remote support server **120**.

In another example use case, the auxiliary sensor array **204** includes sensors that enable detection of hydroplaning as it occurs. If hydroplaning is detected, the transformation module **208** may account for the drastically reduced friction coefficient by normalizing commands received from the remote support server **120** (for instance, by disabling abrupt accelerations and by limiting the maximum steering angle). In other embodiments, the transformation module **208** may also precompute a maximum allowed speed that is likely to enable the vehicle **102** to avoid entering into a hydroplaning situation, or to automatically perform maneuvers designed to exit a hydroplaning situation.

In another example use case, the auxiliary sensor array **204** includes sensors for determining whether the wheels are currently on a typical road surface or an atypical surface with mechanical properties different from those expected (e.g., if the vehicle **102** is veering off the road). If such a situation is detected, the transformation module **208** may normalize control commands by differentially amplifying torques applied to the affected wheel or wheels, if possible, or by varying the yaw angle in a range that may allow the vehicle **102** to retain its offset relative to the central axis of the road in an acceptable range. In other embodiments, the transformation module **208** may cause the vehicle **102** to automatically perform a maneuver to return the vehicle **102** to a road with the typical road surface.

In another example use case, the auxiliary sensor array **204** includes visibility sensors to determine the current visibility conditions as applicable to the front camera, LIDAR and sonar, and to the occupants of the vehicle **102**. The vehicle stabilization module **320** may detect if the visibility drops below a threshold and cause the auxiliary actuator array **322** to take actions such as engaging the windshield wipers, engaging a camera lens wiper, engaging the car lights, adjusting the camera ISO or exposure, engaging fog lights, or other actions. Alternatively, or in addition, the transformation module **208** may transform the received commands by limiting the maximum speed and controlling the distance to a leading vehicle.

In another embodiment, the at least one of the transformation module **208** and the vehicle stabilization module **320** may be instantiated at the remote support server **120** in addition or instead of being within the vehicle **102** at the vehicle normalization system **104**. In this embodiment, the auxiliary sensor data **218** may be transmitted to the remote support server **120** alongside primary sensor data **212** via the wireless networks **140** over shared data channels or over dedicated data channels for processing at the remote support server **120**. Furthermore, in this embodiment, the remote support server **120** may generate auxiliary control commands **324** that control the auxiliary actuator array **322**.

In another embodiment, the transformation module **208**, the vehicle stabilization module **320**, or both may be executed on a networked remote normalization computer that is separate from the remote support server **120**. For example, the transformation module **208** may be executed on a computer that is a part of the roadside infrastructure possessing a short network path to the vehicle **102**. Such an embodiment may allow utilization of hardware that would violate power budget, mass, or other constraints imposed by the design of the vehicle **102**. In this embodiment, the networked remote normalization computer may receive the primary control commands **214** from the remote support server **120** and/or auxiliary sensor data **218** from a vehicle **102**. The networked remote normalization computer may then generate transformed control commands **216** for controlling a primary actuator array **210** of the vehicle **102** and/or auxiliary control commands **324** for controlling an auxiliary actuator array **322** of the vehicle **102**. The commands **216**, **324** may be transmitted to the vehicle **102** to be applied by the vehicle **102** or may be transmitted to the remote support server **120** to enable teleoperation based on the commands.

In a further embodiment, the dedicated networked remote normalization computer comprising the transformation module **208**, the vehicle stabilization module **320**, or both may be utilized to serve multiple vehicles **102** simultaneously. For example, changes in environmental conditions due to wet road surface may affect multiple vehicles **102** navigating the affected segment of the road network. Thus, the multiple vehicles **102** may benefit from a similar or an identical transformation procedure for the control commands **214**. Such remote computers may be run by one or more third parties, with outputs being chained from one normalization computer to another depending on their capabilities.

Reference in the specification to "one embodiment" or to "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiments is included in at least one embodiment. The appearances of the phrase "in one embodiment" or "an embodiment" in various places in the specification are not necessarily all referring to the same embodiment.

Some portions of the detailed description are presented in terms of algorithms and symbolic representations of operations on data bits within a computer memory. These algorithmic descriptions and representations are the means used by those skilled in the data processing arts to most effectively convey the substance of their work to others skilled in the art. An algorithm is here, and generally, conceived to be a self-consistent sequence of steps (instructions) leading to a desired result. The steps are those requiring physical manipulations of physical quantities. Usually, though not necessarily, these quantities take the form of electrical, magnetic or optical signals capable of being stored, transferred, combined, compared and otherwise manipulated. It is convenient at times, principally for reasons of common usage, to refer to these signals as bits, values, elements, symbols, characters, terms, numbers, or the like. Furthermore, it is also convenient at times, to refer to certain arrangements of steps requiring physical manipulations or transformation of physical quantities or representations of physical quantities as modules or code devices, without loss of generality.

However, all of these and similar terms are to be associated with the appropriate physical quantities and are merely convenient labels applied to these quantities. Unless specifically stated otherwise as apparent from the following discussion, it is appreciated that throughout the description, discussions utilizing terms such as "processing" or "computing" or "calculating" or "determining" or "displaying" or "determining" or the like, refer to the action and processes of a computer system, or similar electronic computing device (such as a specific computing machine), that manipulates and transforms data represented as physical (electronic) quantities within the computer system memories or registers or other such information storage, transmission or display devices.

Certain aspects of the embodiments include process steps and instructions described herein in the form of an algorithm. It should be noted that the process steps and instructions of the embodiments can be embodied in software, firmware or hardware, and when embodied in software, could be downloaded to reside on and be operated from different platforms used by a variety of operating systems. The embodiments can also be in a computer program product which can be executed on a computing system.

The embodiments also relate to an apparatus for performing the operations herein. This apparatus may be specially constructed for the purposes, e.g., a specific computer, or it may comprise a computer selectively activated or reconfigured by a computer program stored in the computer. Such a computer program may be stored in a computer readable storage medium, such as, but is not limited to, any type of disk including floppy disks, optical disks, CD-ROMs, magnetic-optical disks, read-only memories (ROMs), random access memories (RAMs), EPROMs, EEPROMs, magnetic or optical cards, application specific integrated circuits (ASICs), or any type of media suitable for storing electronic instructions, and each coupled to a computer system bus. Memory can include any of the above and/or other devices that can store information/data/programs and can be transient or non-transient medium, where a non-transient or non-transitory medium can include memory/storage that stores information for more than a minimal duration. Furthermore, the computers referred to in the specification may include a single processor or may be architectures employing multiple processor designs for increased computing capability.

The algorithms and displays presented herein are not inherently related to any particular computer or other apparatus. Various systems may also be used with programs in accordance with the teachings herein, or it may prove convenient to construct more specialized apparatus to perform the method steps. The structure for a variety of these systems will appear from the description herein. In addition, the embodiments are not described with reference to any particular programming language. It will be appreciated that a variety of programming languages may be used to implement the teachings of the embodiments as described herein, and any references herein to specific languages are provided for disclosure of enablement and best mode.

Throughout this specification, some embodiments have used the expression "coupled" along with its derivatives. The term "coupled" as used herein is not necessarily limited to two or more elements being in direct physical or electrical contact. Rather, the term "coupled" may also encompass two or more elements are not in direct contact with each other, but yet still co-operate or interact with each other, or are structured to provide a thermal conduction path between the elements.

Likewise, as used herein, the terms "comprises," "comprising," "includes," "including," "has," "having" or any other variation thereof, are intended to cover a non-exclusive inclusion. For example, a process, method, article, or apparatus that comprises a list of elements is not necessarily limited to only those elements but may include other elements not expressly listed or inherent to such process, method, article, or apparatus.

In addition, use of the "a" or "an" are employed to describe elements and components of the embodiments herein. This is done merely for convenience and to give a general sense of embodiments. This description should be read to include one or at least one and the singular also includes the plural unless it is obvious that it is meant otherwise. The use of the term and/or is intended to mean any of: "both", "and", or "or."

In addition, the language used in the specification has been principally selected for readability and instructional purposes, and may not have been selected to delineate or circumscribe the inventive subject matter. Accordingly, the disclosure of the embodiments is intended to be illustrative, but not limiting, of the scope of the embodiments.

While particular embodiments and applications have been illustrated and described herein, it is to be understood that the embodiments are not limited to the precise construction and components disclosed herein and that various modifications, changes, and variations may be made in the arrangement, operation, and details of the methods and apparatuses of the embodiments without departing from the spirit and scope of the embodiments.

The invention claimed is:

1. A method for controlling a vehicle comprising:

obtaining primary sensor data from a primary sensor array of a vehicle;

communicating the primary sensor data over a network to a remote support server;

receiving from the remote support server over the network, control commands for controlling a drive system of the vehicle;

obtaining auxiliary sensor data from a local auxiliary sensor array of the vehicle representing environmental conditions local to the vehicle;

locally at the vehicle, applying a transformation to the control commands received from the remote support server that transforms the control commands based on the locally obtained auxiliary sensor data to generate transformed control commands; and

controlling a primary actuator array based on the transformed control commands to control driving of the vehicle.

2. The method of claim **1**, wherein applying the transformation comprises:

applying a machine-learned model to the control commands and the auxiliary sensor data, wherein the machine-learned model is trained based on previously observed handling characteristics of the vehicle in response to previously observed control commands under previously observed environmental conditions.

3. The method of claim **1**, wherein applying the transformation comprises:

applying an analytical model to the control commands that transforms the control commands based on the auxiliary sensor data.

4. The method of claim **1**, wherein the auxiliary sensor data includes at least one set of auxiliary data different from the primary sensor data, wherein the auxiliary data is available locally at the vehicle and is not provided to the remote support server.

5. The method of claim **1**, wherein transforming the control commands comprises transforming at least one a steering command, an acceleration command, and a braking command.

6. The method of claim **1**, further comprising:

determining, based on the auxiliary sensor data, that a state parameter of the vehicle is outside a predefined range;

generating vehicle stabilization commands that operate to restore the state parameter to within the predefined range; and

controlling an auxiliary actuator array to execute the vehicle stabilization commands.

7. The method of claim **6**, wherein the auxiliary actuator array includes at least one actuator that is not under direct control of the remote support server.

8. The method of claim **1**, wherein applying the transformation comprises:

transforming first control commands;

determining, based on the auxiliary sensor data, an error between planned motion of the vehicle and sensed motion of the vehicle;

updating a parameter of the transformation based on the error; and

transforming second control commands based on the updated parameter.

9. A non-transitory computer-readable storage medium storing instructions for controlling a vehicle, the instructions when executed causing one or more processors to perform steps including:

obtaining primary sensor data from a primary sensor array of a vehicle;

communicating the primary sensor data over a network to a remote support server;

receiving from the remote support server over the network, control commands for controlling a drive system of the vehicle;

obtaining auxiliary sensor data from a local auxiliary sensor array of the vehicle representing environmental conditions local to the vehicle;

locally at the vehicle, applying a transformation to the control commands received from the remote support server that transforms the control commands based on the locally obtained auxiliary sensor data to generate transformed control commands; and

controlling a primary actuator array based on the transformed control commands to control driving of the vehicle.

10. The non-transitory computer-readable storage medium of claim **9**, wherein applying the transformation comprises:

applying a machine-learned model to the control commands and the auxiliary sensor data, wherein the machine-learned model is trained based on previously observed handling characteristics of the vehicle in response to previously observed control commands under previously observed environmental conditions.

11. The non-transitory computer-readable storage medium of claim **9**, wherein applying the transformation comprises:

applying an analytical model to the control commands that transforms the control commands based on the auxiliary sensor data.

12. The non-transitory computer-readable storage medium of claim **9**, wherein the auxiliary sensor data includes at least one set of auxiliary data different from the primary sensor data, wherein the auxiliary data is available locally at the vehicle and is not provided to the remote support server.

13. The non-transitory computer-readable storage medium of claim **9**, wherein transforming the control commands comprises transforming at least one a steering command, an acceleration command, and a braking command.

14. The non-transitory computer-readable storage medium of claim **9**, wherein the instructions when executed further cause the one or more processors to perform steps including:

determining, based on the auxiliary sensor data, that a state parameter of the vehicle is outside a predefined range;

generating vehicle stabilization commands that operate to restore the state parameter to within the predefined range; and

controlling an auxiliary actuator array to execute the vehicle stabilization commands.

15. The non-transitory computer-readable storage medium of claim **14**, wherein the auxiliary actuator array includes at least one actuator that is not under direct control of the remote support server.

16. The non-transitory computer-readable storage medium of claim **9**, wherein applying the transformation comprises:

transforming first control commands;

determining, based on the auxiliary sensor data, an error between planned motion of the vehicle and sensed motion of the vehicle;

updating a parameter of the transformation based on the error; and

transforming second control commands based on the updated parameter.

17. A vehicle comprising:

a vehicle drive system including a primary actuator array;

a primary sensor array for sensing primary sensor data;

an auxiliary sensor array for sensing auxiliary sensor data;

one or more processors; and

a non-transitory computer-readable storage medium storing instructions for controlling the vehicle drive system, the instructions when executed causing the one or more processors to perform steps including:

obtaining the primary sensor data from the primary sensor array;

communicating the primary sensor data to a remote support server;

receiving from the remote support server, control commands for controlling the vehicle drive system;

obtaining the auxiliary sensor data from the auxiliary sensor array representing environmental conditions local to the vehicle;

locally at the vehicle, applying a transformation to the control commands received from the remote support server that transforms the control commands based on the auxiliary sensor data to generate transformed control commands; and

controlling the primary actuator array of the vehicle drive system based on the transformed control commands to control driving of the vehicle.

18. The vehicle of claim **17**, wherein applying the transformation comprises:

applying a machine-learned model to the control commands and the auxiliary sensor data, wherein the machine-learned model is trained based on previously observed handling characteristics of the vehicle in response to previously observed control commands under previously observed environmental conditions.

19. The vehicle of claim **17**, wherein applying the transformation comprises:

applying an analytical model to the control commands that transforms the control commands based on the auxiliary sensor data.

20. The vehicle of claim **17**, wherein the auxiliary sensor data includes at least one set of auxiliary data different from the primary sensor data, wherein the auxiliary data is available locally at the vehicle and is not provided to the remote support server.

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